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Citation for published version (APA):
Kappatou, A., Delabie, E., Jaspers, R. J. E., & von Hellermann, M. G. (2011). Feasibility of charge exchange spectroscopy fast helium measurements on ITER. In *38th EPS Conference on Plasma Physics 2011, EPS 2011 - Europhysics Conference Abstracts* (Vol. 35 1, pp. 769-772)

Document status and date:
Published: 01/12/2011

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Feasibility of Charge Exchange Spectroscopy fast helium measurements on ITER

A. Kappatou[1], E. Delabie[1], R.J.E. Jaspers[2], M.G. von Hellermann[1]

[1] *FOM Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Nieuwegein, The Netherlands*

[2] *Science and Technology of Nuclear Fusion, Eindhoven University of Technology, The Netherlands*

Abstract

The feasibility to measure fast alpha particles using Active Charge Exchange Recombination Spectroscopy (CXRS) on ITER is investigated. Through modelling of the charge exchange spectral line for fast ions together with the expected background emission, the signal-to-noise ratio has been calculated as a function of the diagnostic design parameters. Combining the CXRS data from both the heating and the diagnostic neutral beams on ITER, information on the fast ion energy spectrum up to 1 MeV can be obtained for the parameters of the ITER core CXRS diagnostic design, provided that the signal is binned in 100 keV bins and a time resolution of 1sec is used.

Introduction

ITER will be the first burning plasma physics experiment with dominant alpha particle heating. In this operating regime, the study of issues relevant to the fusion produced energetic alpha particles, such as fast ion transport and interaction with plasma instabilities will be a main priority. Therefore, according to ITER requirements, the energy spectrum and density profiles of confined alphas of 0.1 to 3.5 MeV should be measured with an accuracy of 20%, with a time resolution of 100ms and a spatial resolution of a/10 [1].

Two diagnostics that can potentially provide information on fast alphas are Collective Thomson Scattering and Charge Exchange Recombination Spectroscopy, but both are limited by the fact that an inversion of the measurements to infer the distribution function unambiguously is not possible for a limited number of lines of sight. CXRS is foreseen for ITER to diagnose the thermalized helium ash, and in addition information on fast particles can be found in the wings of the CX spectrum. The technique of fast ion CXRS for beam originating fast ions has been applied successfully at JET[2], TEXTOR[3] and DIII-D[4] and for fusion produced alpha particles at TFTR[5].

The fast helium charge exchange diagnostic on ITER will be characterized by the small spectral signal in comparison to the background emission due to the higher bremsstrahlung and larger beam attenuation. In view of this challenging task, in order to assess the feasibility of CX measurements of fast α's on ITER, the active CX fast helium spectrum is modelled.

Simulation of CX fast helium measurements on ITER

Simulation package

A simulation package [6] has been used to assess the feasibility of fast helium CX measurements on ITER. The code provides the observed CX spectrum, taking into account the tokamak and beam geometry, the beam attenuation and plasma emission rates. The plasma and beam parameters are used as input. The instrumentation specifications of a virtual spectrometer allow for the reconstruction of the observed spectrum.

The slowing down distribution functions of alpha particles as well as that of beam originating fast ions can be simulated. This slowing down distribution function is multiplied with the collision energy dependent charge exchange rates. Subsequently, it is projected on a line of sight and then summed up in order to obtain the observed spectral shape. The bremsstrahlung background emission is also calculated and poisson noise is added to the spectra. To evaluate the feasibility of measurements the signal to noise ratio is used as a figure of merit.

Before proceeding with the study of ITER, an attempt was made to benchmark the simulation results of the fast alpha CX spectra against the $\alpha-$CHERS TFTR measurements[5]. The instrument specifications and experiment details mentioned in [5],[7] in combination with the TFTR and beam geometry were used in order to simulate the spectra from the 6MW fusion power shots. For fast alpha particle densities of $\approx 10^{17}m^{-3}$, the simulation code gives a SNR of about 10 (values of 5-10 mentioned in the $\alpha-$CHERS publications) and an intensity of fast helium signal about 1% of the bremsstrahlung level ($< 1\%$ in publications). Consequently, the code is found to evaluate the fast alpha spectrum and noise levels correctly.

Simulation of the alpha CX spectrum

In comparison with TFTR the challenges are immediately apparent. On TFTR the fast helium signal over the bremsstrahlung level was already very low, less than 1%. Due to a much higher bremsstrahlung level, lower beam penetration for the diagnostic beam and lower beam particle flux and directionally very selective cross sections for the heating beam, the signal to noise ratio will be even 100 times worse, despite the fact that the alpha particle density will be 30 times higher on ITER. By increasing the effective throughput of the system, one can try to compensate for this. In order to judge the overall effect for the ITER CX system, a quantitative study has been undertaken.

Using the simulation package, the CX line is calculated together with the expected noise level, with a full spectral resolution of 0.2Å/px. The design parameters of the core CXRS diagnostic for ITER are used: etendue $\varepsilon = 1mm^2sr$, quantum efficiency $QE = 90\%$, optical transmission $T = 5\%$. However, an increased exposure time $t_{exp} = 1s$ is used. The spectra for the diagnostic (DNB, 100keV/amu) and heating (HNB, 500keV/amu) beams are calculated separately and are shown in Fig. 1. Fast alphas of energy up to 0.4MeV can be diagnosed using the DNB, while in the case of the HNB the signal is below noiselevel for all energies. The energy range cannot be extended to 3.5MeV, due to the energy of the available beams.

Subsequently the signal is binned in energy bins and the signal to noise ratio is calculated as

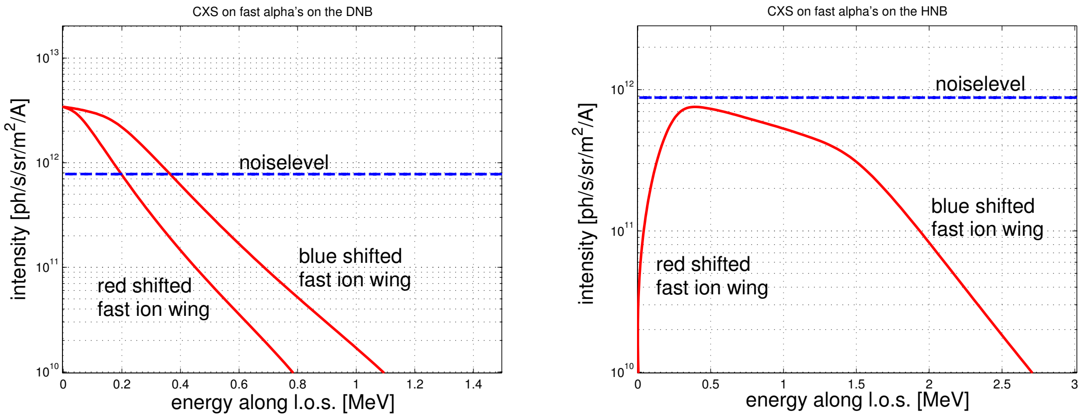

Figure 1: Modelled fast helium slowing down spectra for ITER. On the left, looking to the DNB (100keV/amu, 3.6MW) from upper port 3. On the right, looking to the HNB (500keV/amu, 17MW) from the equatorial port 3. The expected noise level per pixel on full spectral resolution is also shown. Parameters used: $\eta = \varepsilon t_{exp} QET = 0.045 mm^2 srs$, $\rho = 0.5$, $n_e = 10^{20}(1-\rho^2)^{0.1} m^{-3}$,$T_e = 25(1-\rho^2)^{0.5} keV$,$T_e = 21(1-\rho^2)^{0.8} keV$ and $P_{fusion} = 600MW$.

a function of the effective optical throughput $\eta = \varepsilon t_{exp} QET$. This is the part of the SNR that is determined by the diagnostic design. The SNR as a function of η is plotted in Fig. 2 for DNB and HNB and for the different energy beams.

Assuming that a SNR of about 10 is needed for reliable measurements, this can be obtained for fast alphas of 0.1-1MeV for $\eta = 10^{-7} m^2 srs$ in combination with an energy binning of at least 100keV. To arrive to this value of η, an exposure time of 2sec is needed for the reference values of the CXRS diagnostic design (indicated by the dashed line on the left).

A better time resolution could be obtained for a higher etendue. Nonetheless, there is an upper limit for the etendue that can be achieved on the tokamak side. Assuming a mirror diameter of 10cm, a 10cm beam spot size and a 4m path length, maximum etendue is $3.8 mm^2 sr$. Stretching the design to the optimum, i.e. using the maximum etendue and an improved transmission of 15% (indicated in Fig. 2 by the dashed line on the right), a SNR=10 can be obtained for alpha particles up to 1MeV of energy with a better exposure time of 200ms.

A similar study has been conducted for JET in the case of a future D-T campaign. Using the standard equatorial charge exchange diagnostic, measurements of alpha particles of energy up to 600keV can be obtained, with an energy resolution of 100keV and a time resolution of 1 sec, taking into account the neutral beams enhancement. A higher optical throughput system will be needed for better time and energy resolution.

Discussion

The feasibility of CXRS measurements of fast helium on ITER is certainly much less optimistic than previous studies have assumed: In [8] fast helium CX measurements on ITER are discussed, but the SNR mentioned are from calculations regarding thermal helium. Simulated fast alpha spectra and noise levels are also published in [9], mentioning a SNR=5 at 5ms time resolution. However, the etendue of $25 mm^2 sr$ that is used for the calculations is too large, as

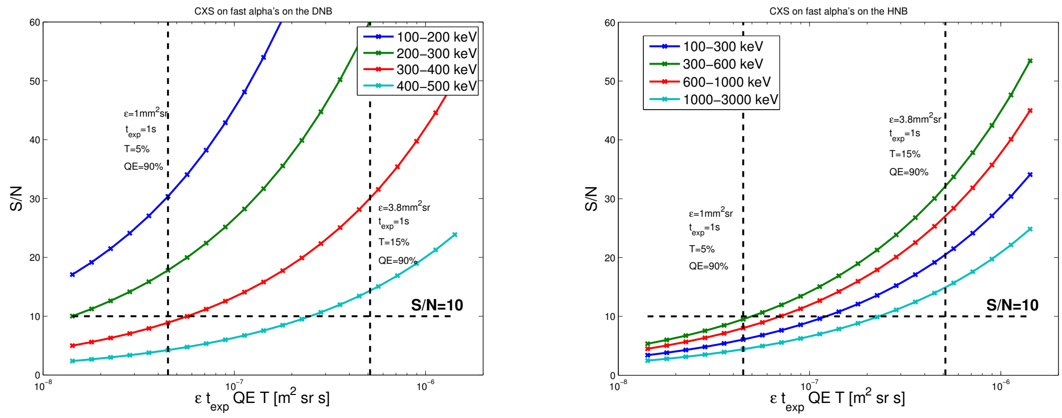

Figure 2: The signal to noise ratio for CXRS on fast helium when the signal is binned over a number of energy bins is plotted versus the effective optical throughput of the diagnostic, for CX between fast helium and DNB (on the left) and between fast alphas and HNB (on the right). The reference and limiting values for the core CXRS design are indicated by dashed lines.

discussed in the previous section. No spectral resolution is mentioned and the bremsstrahlung level was underestimated by a factor of $10^{3/2}$ due to a miscalculation in the code, resulting in a SNR 5.6 times higher.

It should be made clear that there are more issues not taken into account in this study. There is a possibility of impurity lines in the wavelength of interest, adding to the background emission, which will lead in a further reduction of SNR and a much harder choice of impurity free wavelength bins. Reflections on the metallic wall would deteriorate the situation.

From this work, it can be concluded that both DNB and HNB will be needed for fast helium measurements on ITER. However, no information will be provided on fast ions of energy larger than 1MeV due to the beam energy. The fast alphas CX measurements do not come for free: the effective optical throughput η has to be improved in respect to the thermal CXRS diagnostic, making the need of a dedicated system much stronger. Even in the best case though, there is still a limit on the SNR that can be achieved. The ITER requirements for energy and time resolution cannot be achieved. The SNR could be improved however with the use of better focused neutral beams. Nevertheless, steady state fast helium density profiles can be examined with CXRS.

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